新物理与暗物质理论综述

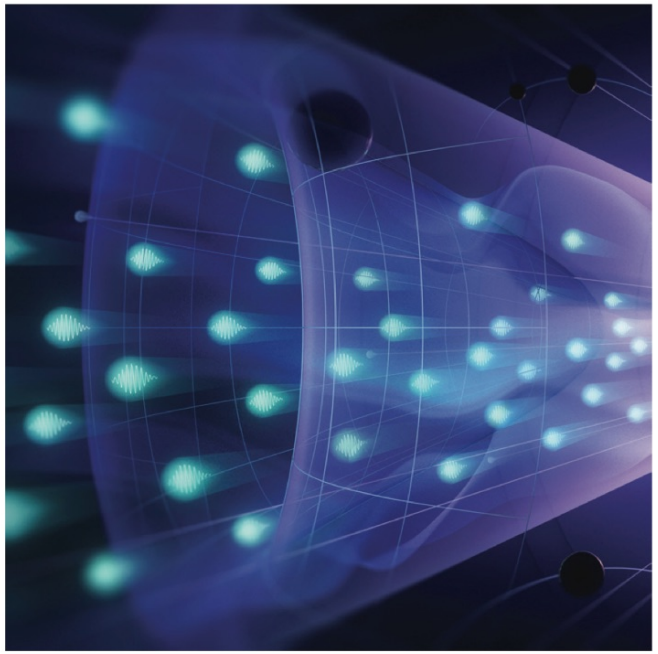
Review of New Physics and Dark Matter Theories

鲜于中之 [Zhong-Zhi Xianyu]

清华大学物理系 [Dept. of Physics, Tsinghua University]

中国物理学会高能物理分会第十四届全国粒子物理学术会议

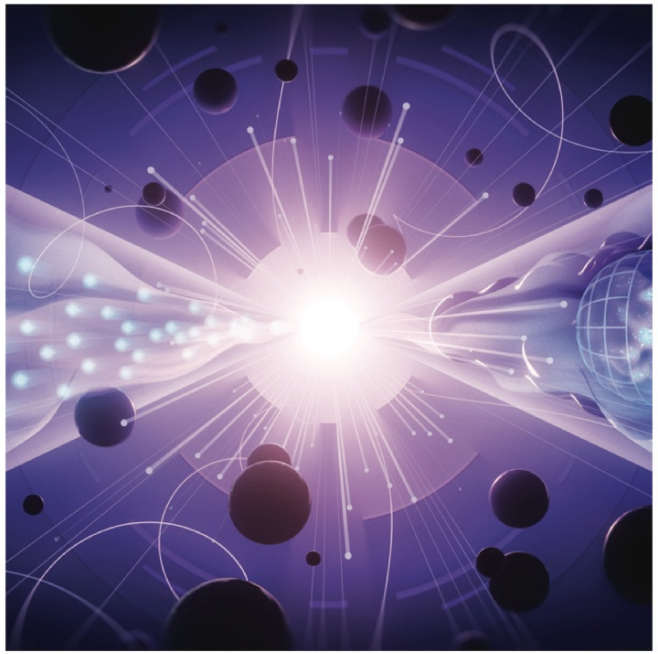
青岛 | 2024年8月14日



Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

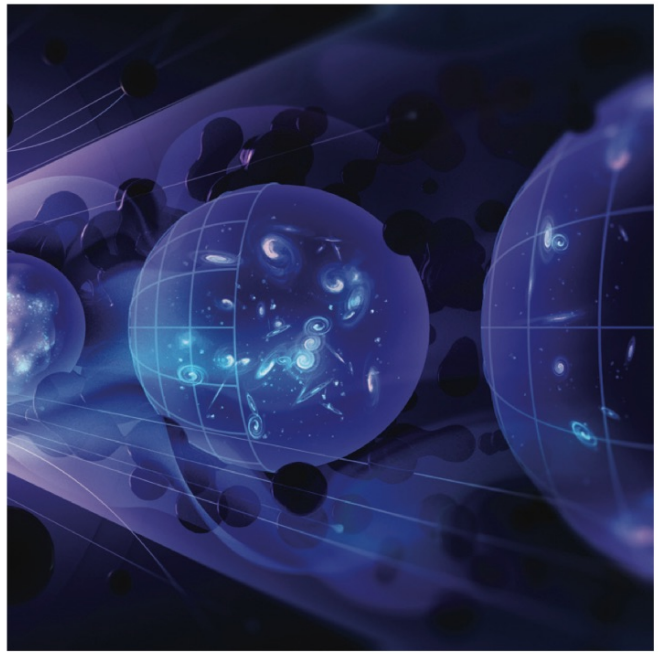
Reveal the Secrets of the Higgs Boson



Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena



Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

From the Report of the 2023 Particle Physics Project Prioritization Panel

BSM New physics must exist

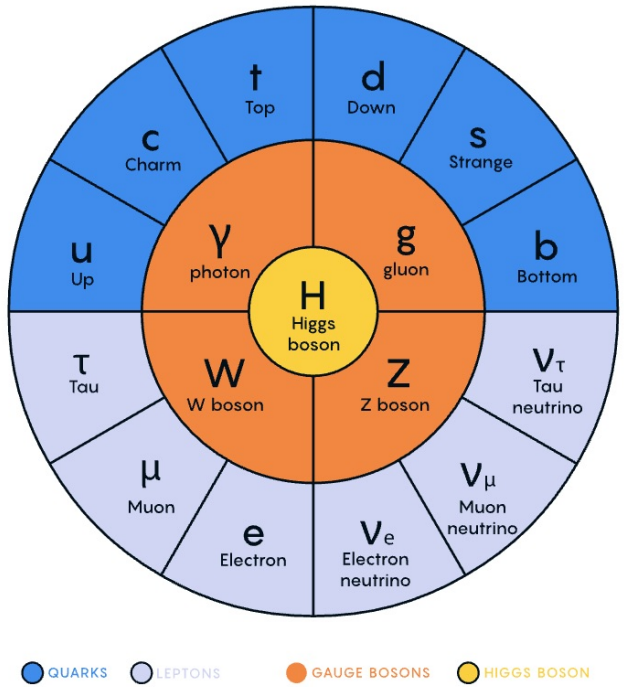


Image credit: *Particle Fever* (2013)

The Standard Model

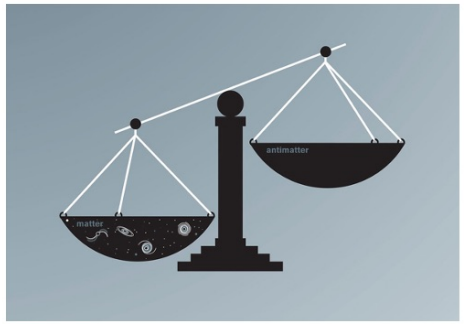
glorious triumph below TeV
exceedingly unsatisfactory at higher scales

We should vigorously push the UV cutoff scale
@ both energy & precision frontiers!

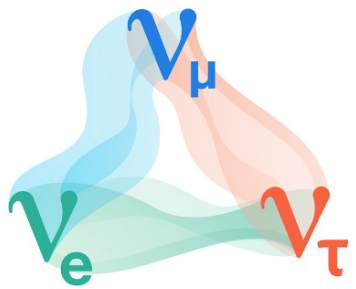
Also see talks by Yanwen Liu on TeV, Wenbin Qian and Fusheng Yu on flavor
More talks by Antonios Agapitos, Yuchen Cai, Boxing Gou, Haifeng Li, Jingshu Li, Jinmian Li, Shu Li, Danning Liu, Yang Liu, Feng Lyu, Wei Su, Yilei Tang, Junquan Tao, Ngoc Khanh Vu, Zebing Wang, Xinkai Wen, Zhengyun You, Rui Yuan, Yixiang Zhang, Chen Zhou, etc.

BSM New physics must exist

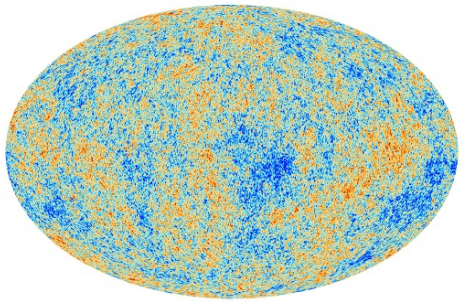
Dark matter



matter-antimatter asymmetry



Neutrino oscillation



Large scale structure

Talks by Ke Han, Jiajie Ling, Xunjie Xu, and many more

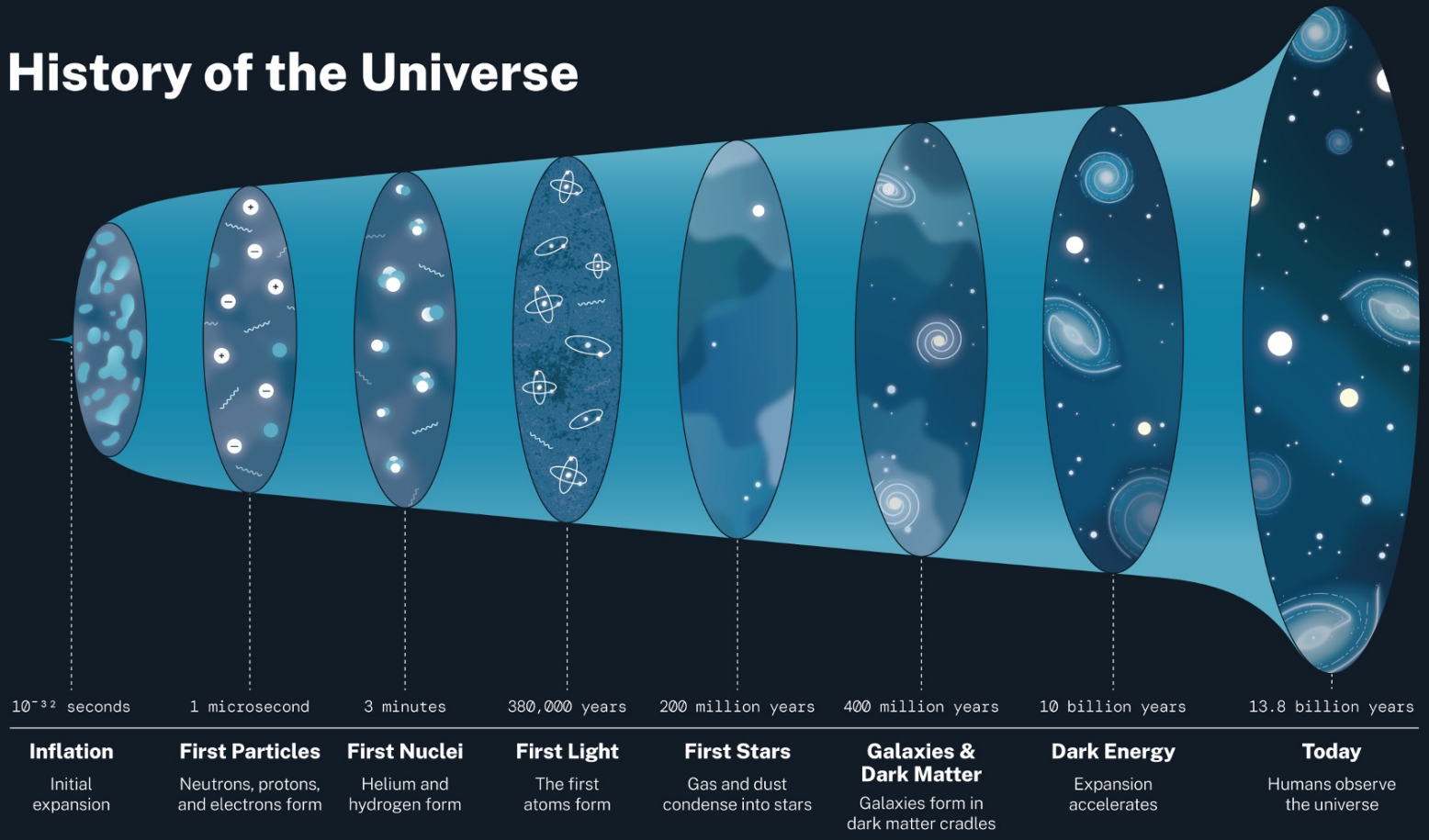
More importantly:

We have solid evidences of BSM physics, all originated from astro/cosmo probes

Also, SM doesn't include gravity

Image credit: DUNE, ESA, LEGEND

Cosmology: a gold mine of BSM physics



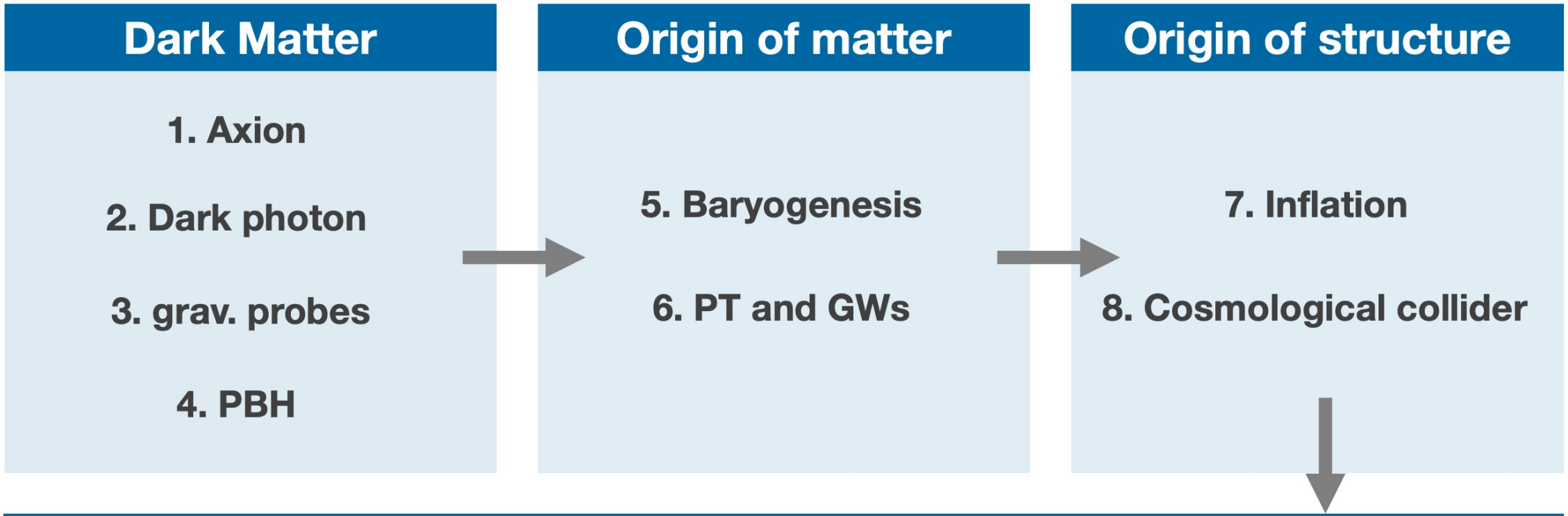
3. Origin of structure

2. Origin of matter

1. Dark matter

Image credit: NASA

Outline


Dark Matter
1. Axion
2. Dark photon
3. grav. probes
4. PBH
Origin of matter
5. Baryogenesis
6. PT and GWs
Origin of structure
7. Inflation
8. Cosmological collider
New languages & new methodologies
9. QFT tools for cosmology
10. Generalized symmetry
11. Quantum & HEP

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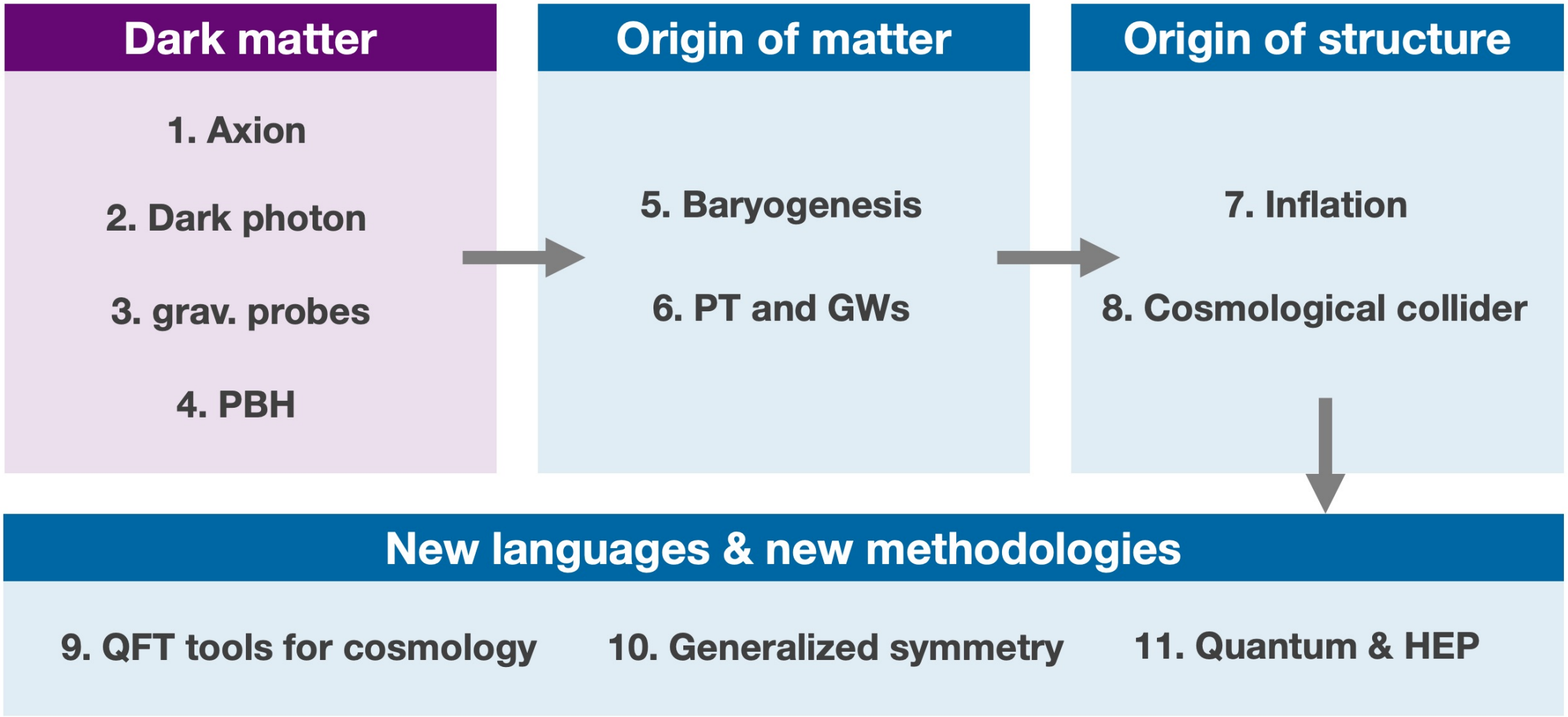
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Dark matter | WIMP and beyond

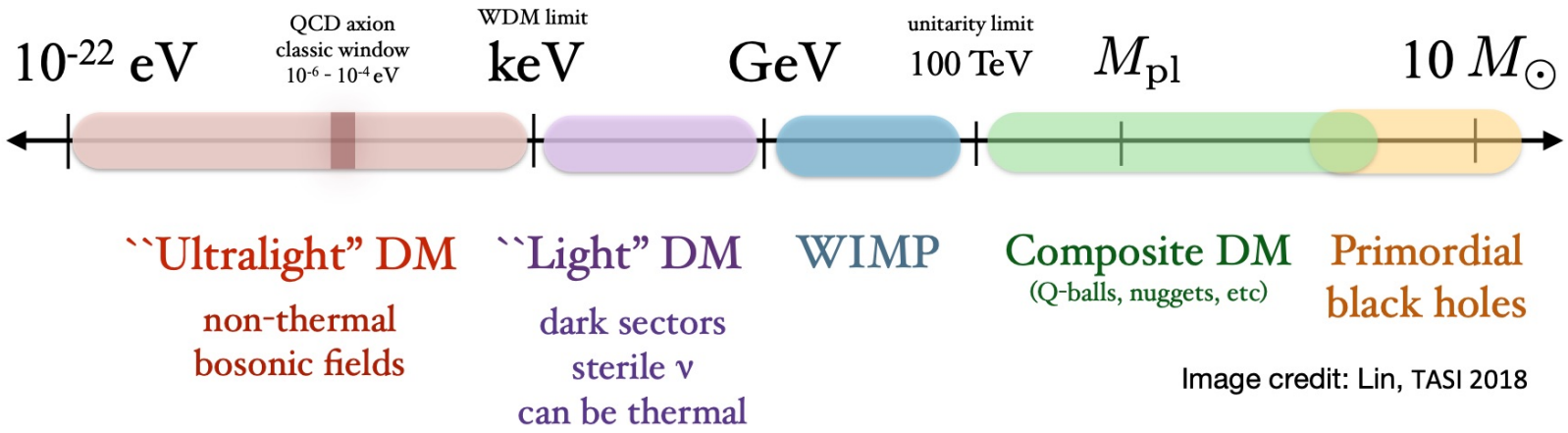


Image credit: Lin, TASI 2018

Many evidences! The existence is without question

Some DM properties known well [abundance, weakly coupled, cold], but the mass known poorly

WIMP remains a leading paradigm for DM, while other scenarios actively pursued too
[axions, dark photons, PBH, composite, SIDM, etc.]

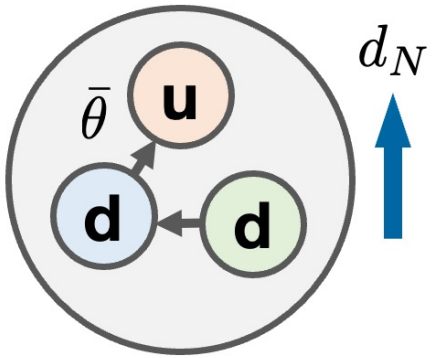
Many interesting topics not covered here
[Millicharged particles, ALP, cosmic birefringence, small-scale anomalies …]

Talks by, Zuowei Liu, Ningqiang Song, Yi Tao, LiTao Yang …

Axion | strong CP and UV models

Neutron EDM is surprisingly tiny!

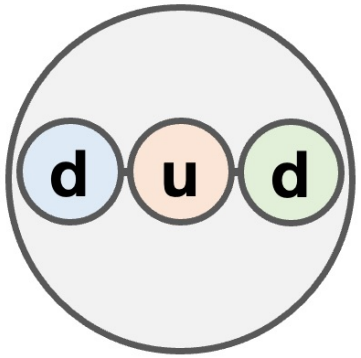
Hook: TASI 2018



d_N

Naïve estimate:

$$|d_n| = 10^{-15}\mathrm{m} \times e$$



Exp limit:

$$|d_n| < 10^{-28}\mathrm{m} \times e$$

$$\bar{\theta} < 10^{-13}$$

In QCD, nEDM from a ~~CP~~ angle:

$$\mathcal{L} = \bar{\theta}\frac{g^2}{32\pi^2}G\tilde{G} \qquad \bar{\theta} = \theta - \arg\det(Y_d Y_u)$$

Strong CP problem:

Why the net CP angle so much smaller than CP phases in CKM?

Solution: Make the theta angle dynamical! => Axion

Two broad categories of axion models:

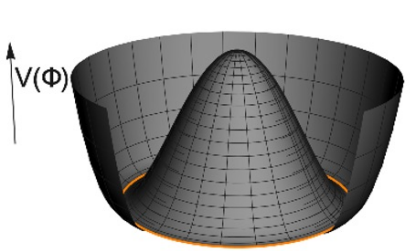
1) Goldstone of a broken anomalous U(1) [PQ]

2) Light mode of extra-dim gauge fields or strings

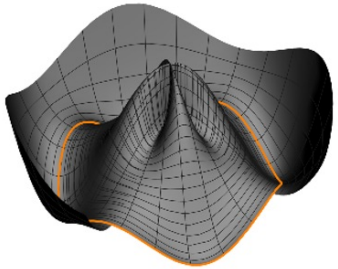
[Reece: 2406.08543]

Axion | cosmology of PQ axion

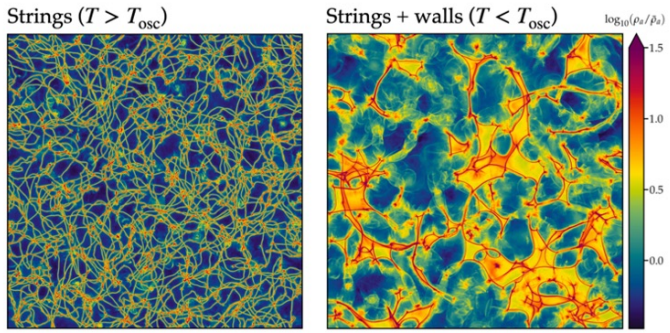
- Typically, axion DM produced from misalignment
- Two classes: pre- and post-inflation PQ breaking
- Pre: Axion homogenized [DM isocurvature problematic?]
  A solution: lift axion during inflation **[Chen, Fan, Li, 2303.03406]**
- Post: Axion randomized; Rich cosmology!
  Axion string, domain wall, minicluster/axion star
  [O'Hare, 2403.17697 for a recent review]
  Axion production from string / DW decay
  [scaling; simulation challenge] **[Harigaya, Wang, 2211.08289]**
  Defects problematic if DW# > 1, in tension with axion quality
  [Lu, Reece, Sun, 2312.07650]
- Extra-dim axion ~ "pre-inflation breaking"
  [Reece: 2406.08543]
- New model building ideas
  Using higher-order terms in the potential; kinetic misalignment
  New possibilities for baryogenesis
  [Co, Hall, Harigaya, 1910.14152 and many more]



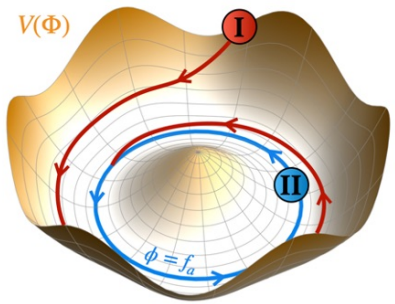
Axion potential after PQ breaking



Axion potential after QCD transition
Image credit: 2105.01406



Axion strings & domain walls
https://github.com/veintemillas/jaxions

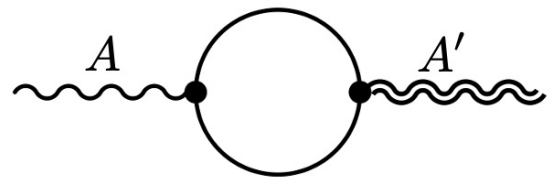


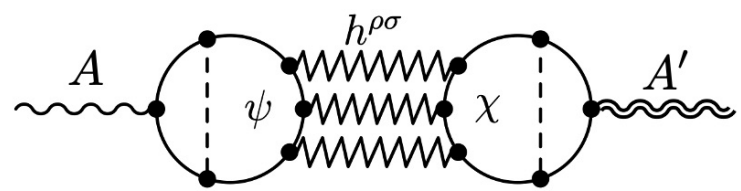
Kinetic misalignment
Image from 2108.10328

Dark photon

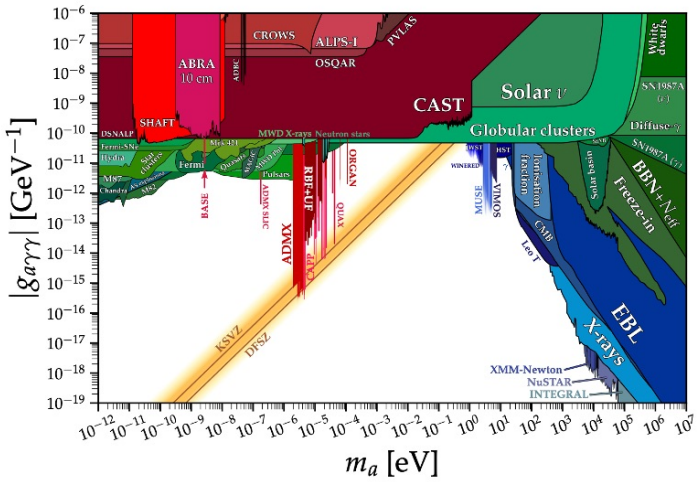
- Spin-1 boson, typically light [below MeV] or massless, weakly coupled to SM
  [kinetic mixing / gauging an unbroken U(1) such as B-L]
  [Cline: 2405.08534 for a recent review]
- Kinetic mixing: Photon <-> DP conversion
- Mass origin: Higgs (H) or Stueckelberg (S)
  If H: Higgs millicharged; new mixing; more constrained
  Richer pheno: vortex string formation etc.
  [East, Huang, 2206.12432 and many more]
  If S: Too small mass in tension with QG **[Reece, 1808.09966]**
- UV models: generated by many portal couplings
  Curiously, gravity mixes A&A' at 6-loop **[Gherghetta+, 1909.00696]**
- DPDM production: Inflation production **[Graham et al., 1504.02102]**
  Axion-driven **[Agrawal+, 1810.07188; Co+, 1810.07196]**
  Parametric resonance **[Dror+, 1810.07195]**

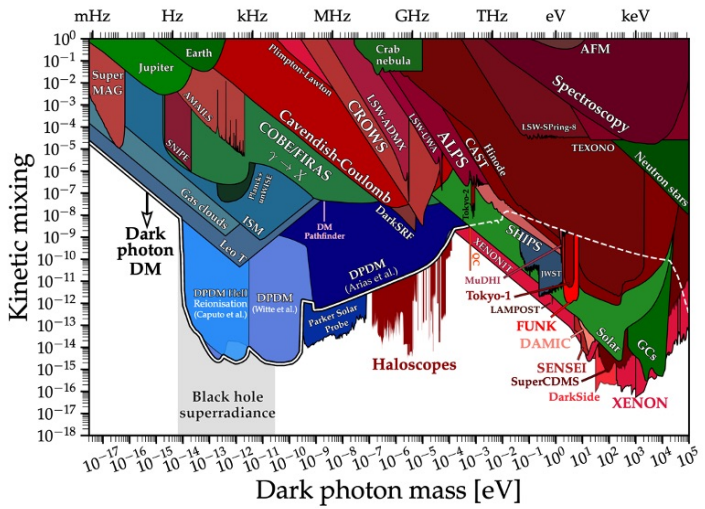
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m^2_{A'}A'_\mu A'^\mu - \frac{1}{2}\epsilon F_{\mu\nu}F'^{\mu\nu}$$





Detection strategy

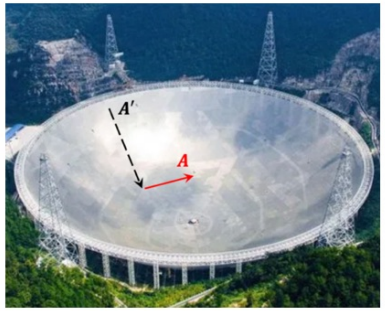


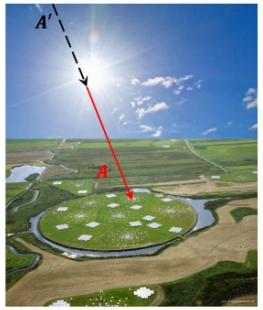


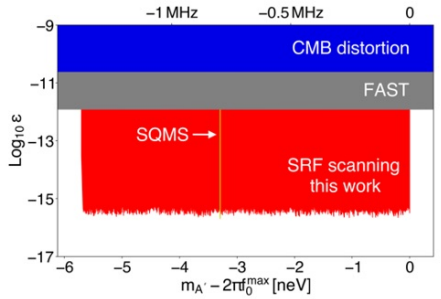
Lab conv, Astro conv, DM

https://github.com/cajohare/AxionLimits

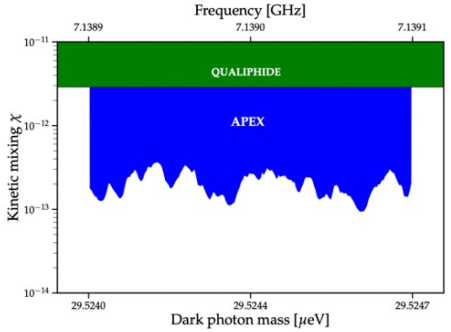
- Lab conversions:
  [SHANHE: 2305.09711, APEX: 2404.00908, etc]
- Dark photon with FAST, LOFAR, JWST, Parker, Gaia
  [An+ 2207.05767, 2301.03622, 2304.01056, 2402.17140, 2405.12285, 2407.16488]
- Astro probes:
  Detecting heavy DM with LHASSO
  [Cao+, 2210.15989, 2406.08698]
  Axion with LHASSO
  [Zhang, Ma, 2210.13120 (axion)]



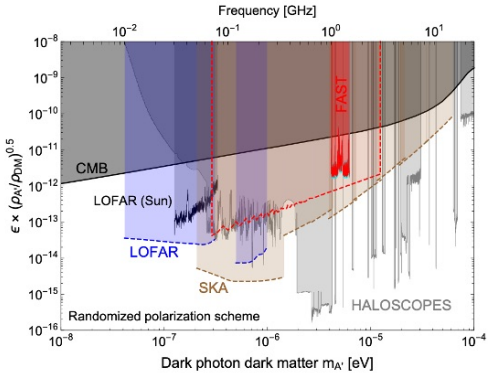




SHANHE: 2305.09711



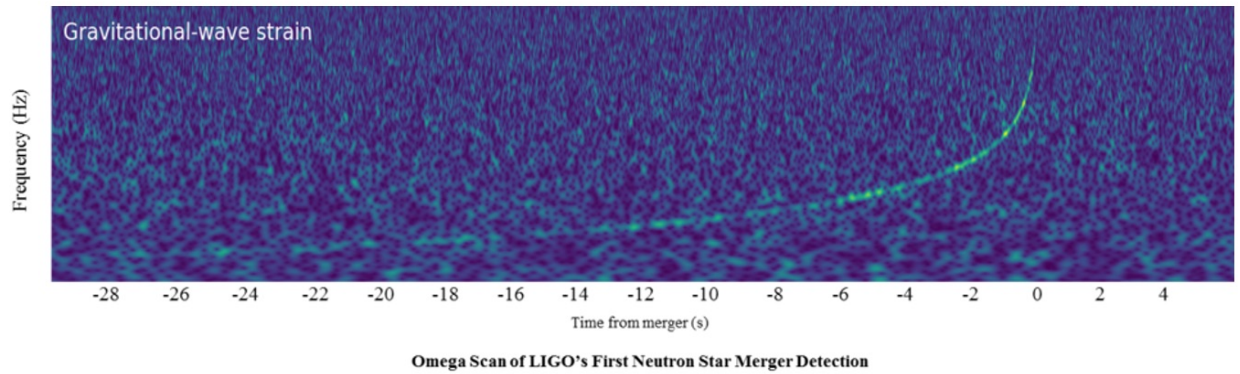
APEX: 2404.00908



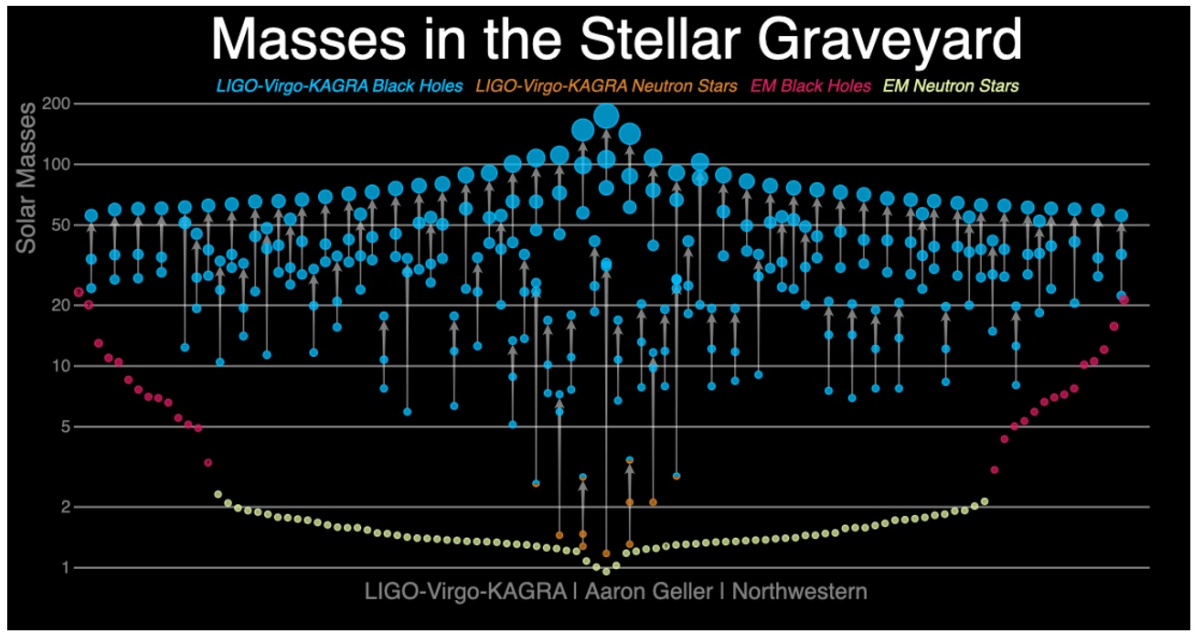
An+, 2207.05767

Precision gravitational probe

- All DM evidences are from gravitation
- Most detection strategies assume beyond gravity couplings --- a gap!
- Why? --- To reveal the particle nature, precision matters!
- Any precision gravitational probes?
- GW as precision probes in two senses:
  Precise waveform (>3PN)
  Increasing statistics
- Example: 5th force search:
  dipole radiation ~ -1PN effect
  [Croon et al., 1711.02096]



Omega Scan of LIGO's First Neutron Star Merger Detection



Superradiance

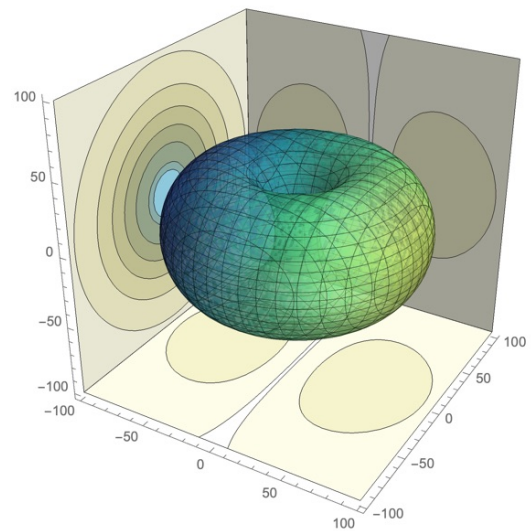
- Spinning BH can trigger production of ultralight bosons
  quantum fluctuation + Penrose process **[Brito+, 1501.06570 for a review]**
- The produced boson could be NR: Gravitational atom
  bound BEC states / hydrogen-like spectrum
  Imaginary part: production and absorption **[Bao, Xu, Zhang, 2201.10941]**
- Rich pheno within a binary
  Landau-Zener transition => floating and sinking orbit
  [Baumann+, 1804.03208, 1912.04932]
  Cloud induced orbit precession **[Su, ZX, Zhang, 2107.13527]**
  Cloud ionization and disruption **[Baumann+, 2112.14777, 2206.01212, Tong, Wang, Zhu, 2205.10527, 2311.17013]**
  Gravitational molecule **[Liu, Lyu, 2107.09971]**
- With non-grav coupling:
  Higgsed dark photon: vortex string formation
  [Siemonsen et al., 2212.09772]
  Axion: constraint from EHT **[Chen+, 1905.02213, 2105.04572]**

$$(\Box - \nu^2)\sigma = 0$$

$$\sigma = 2\mathrm{Re}\frac{1}{\sqrt{2\nu}}\psi_{n\ell m}e^{-\mathrm{i}E_n t}$$

$$E_n = -\frac{\alpha^2\nu}{2n^2}$$

$$\alpha = GM_{\mathrm{BH}}\nu$$



Primordial black holes

- Large primordial curvature fluctuations collapse directly into BHs after reentering the horizon
  [Sasaki et al., 1801.05235, Pi, 2404.06151 for reviews]
- DM candicate / Probe of primordial fluctuations at small scales
- The required large fluctuation can arise at smaller scales
  [large scale strictly constrained by CMB]
- The PBH mass determined by the comoving scale of the peak of the curvature fluctuation (wide range)
- Various constraints for masses across many orders of magnitudes **[Carr, Kuhnel, 2110.02821]**
  [Hawking rad / microlensing / GWs / CMB]

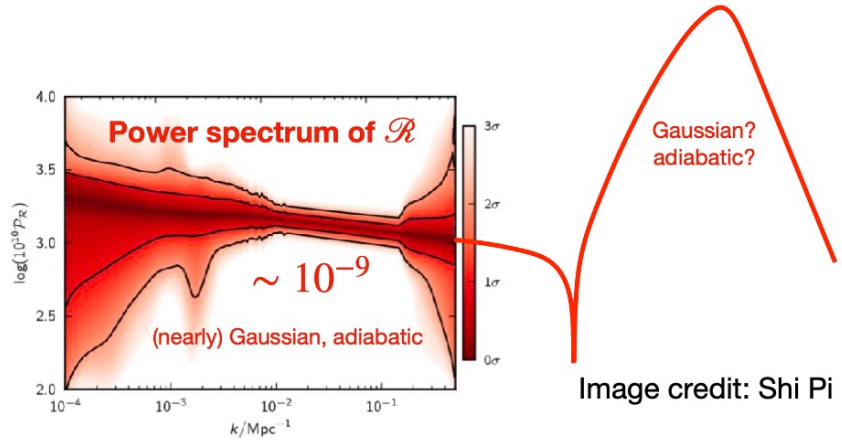
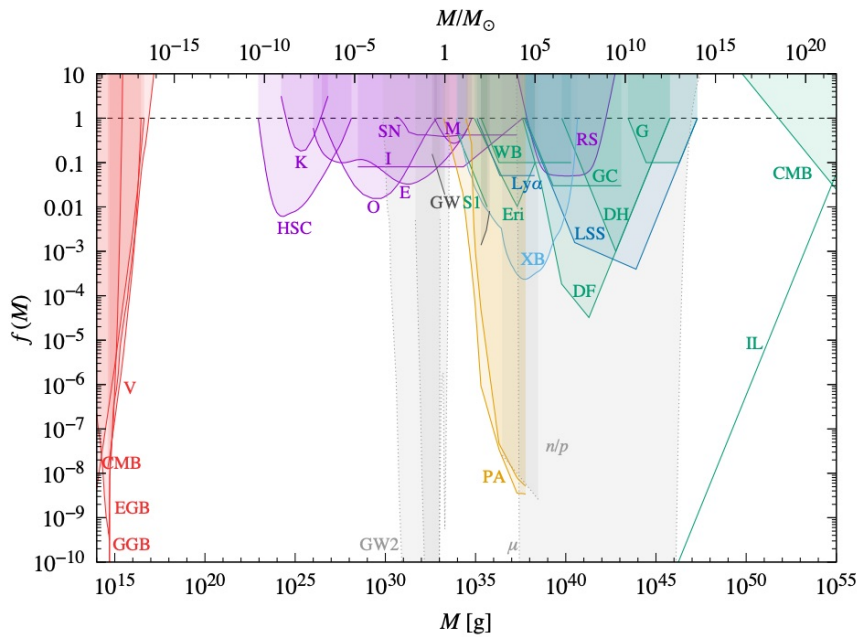


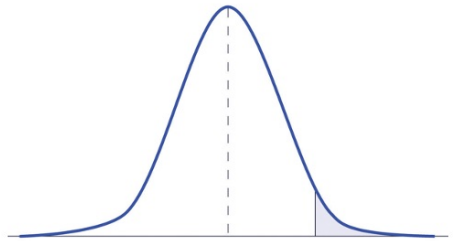
Image credit: Shi Pi



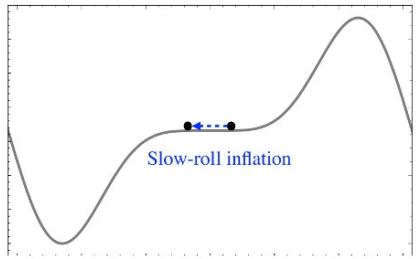
Carr, Kuhnel, 2110.02821

Primordial black holes

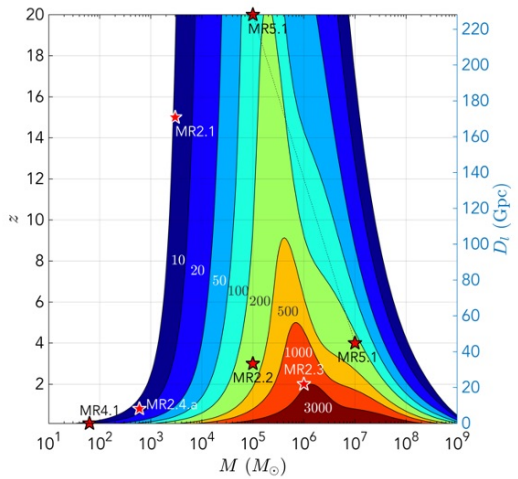
- Challenge 1: Formation highly (exponentially) sensitive to model parameters
  Press-Schechter inadequate, many potentially important effects
- Question: can we identify all (exponentially) important effects?
  [Works by Shi Pi, Sai Wang, etc.]
- Challenge 2: Typically, severe tuning of inflation potential
  [ultra slow-roll inflation, inflection, etc.]
- Question: any “natural” model without severely fine-tuning the potential?
  [New models or new production mechanisms, works by Yingli Zhang, Kepan Xie, Haipeng An, etc.]
- Challenge 3: How to identify PBHs?
  Easy answer: waiting for mHz GW telescopes (Taiji/LISA/Tianqin)
  More nontrivially: PBH of appreciable abundance => Observably large induced GW, robust against non-G **[Cai, Pi, Sasaki, 1810.11000, etc]**



PBH from Gaussian tail

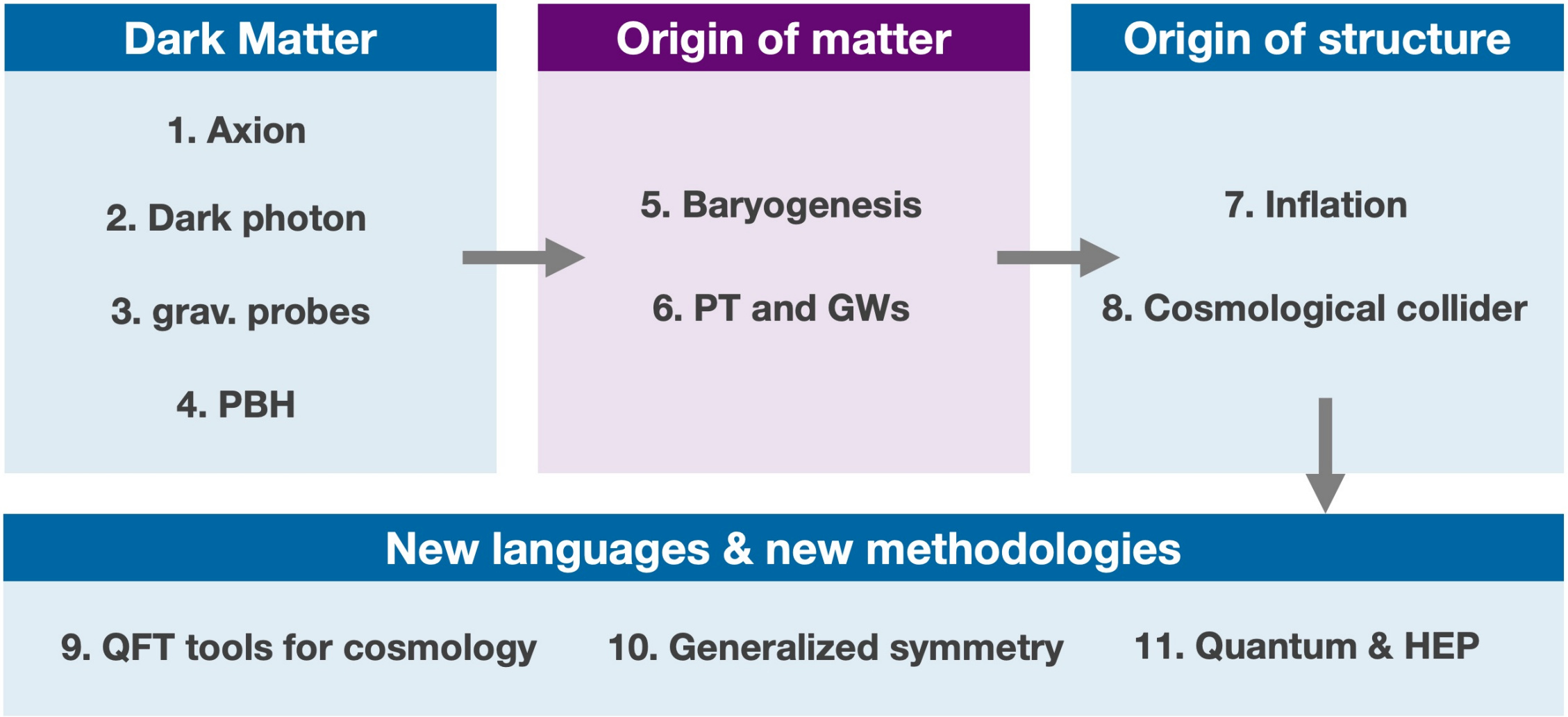


Inflation potential w/ a inflection point



LISA - mission proposal (2017)

Outline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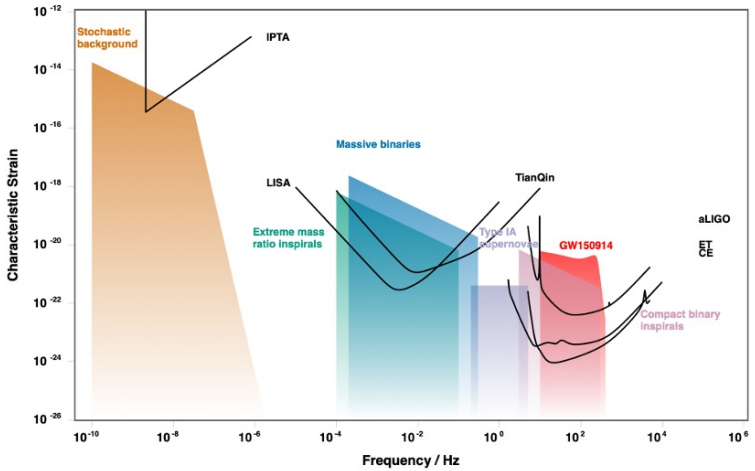
Early-universe phase transitions | Baryogenesis

- Matter-antimatter asymmetry --- slightly more matter than antimmater: $\frac{n_B}{s} \sim 10^{-9}$
- Initial B≠0 incompatible with cosmic inflation: $e^{-50\times 3} \sim 10^{-67}$
- A mechanism bringing the universe from B=0 to B≠0: baryogenesis $\mathrm{d}n_B/\mathrm{d}t \neq 0$
- Three Sakharov conditions must be satisfied simultaneously to have
  ~~B~~ / ~~P~~ & ~~CP~~ / non-equilibrium: All exist in SM, but too weak. BSM is required!
- Typical examples: Electroweak / Leptogenesis / Affleck-Dine / Spontaneous
  Barrie, Han, Murayama 2106.03381, 2204.08202 etc.
- Challenge: Not hard to get a single number right, but typically at very high scales, hard to test
- BG typically accompanied with PT in the early universe. New probes from GWs!

Early-universe phase transitions | GWs



http://gwplotter.com

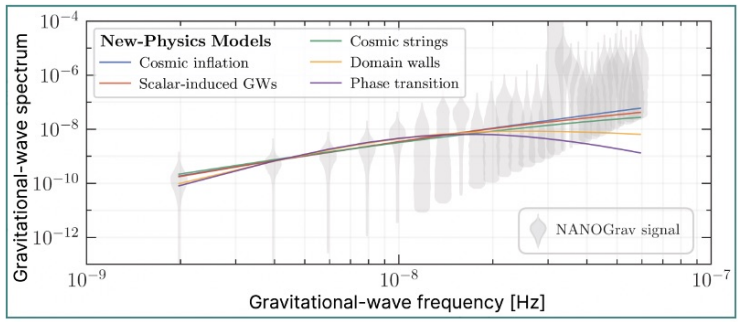
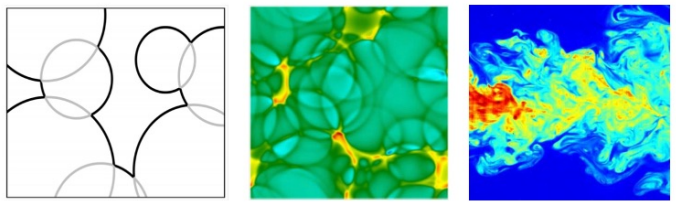


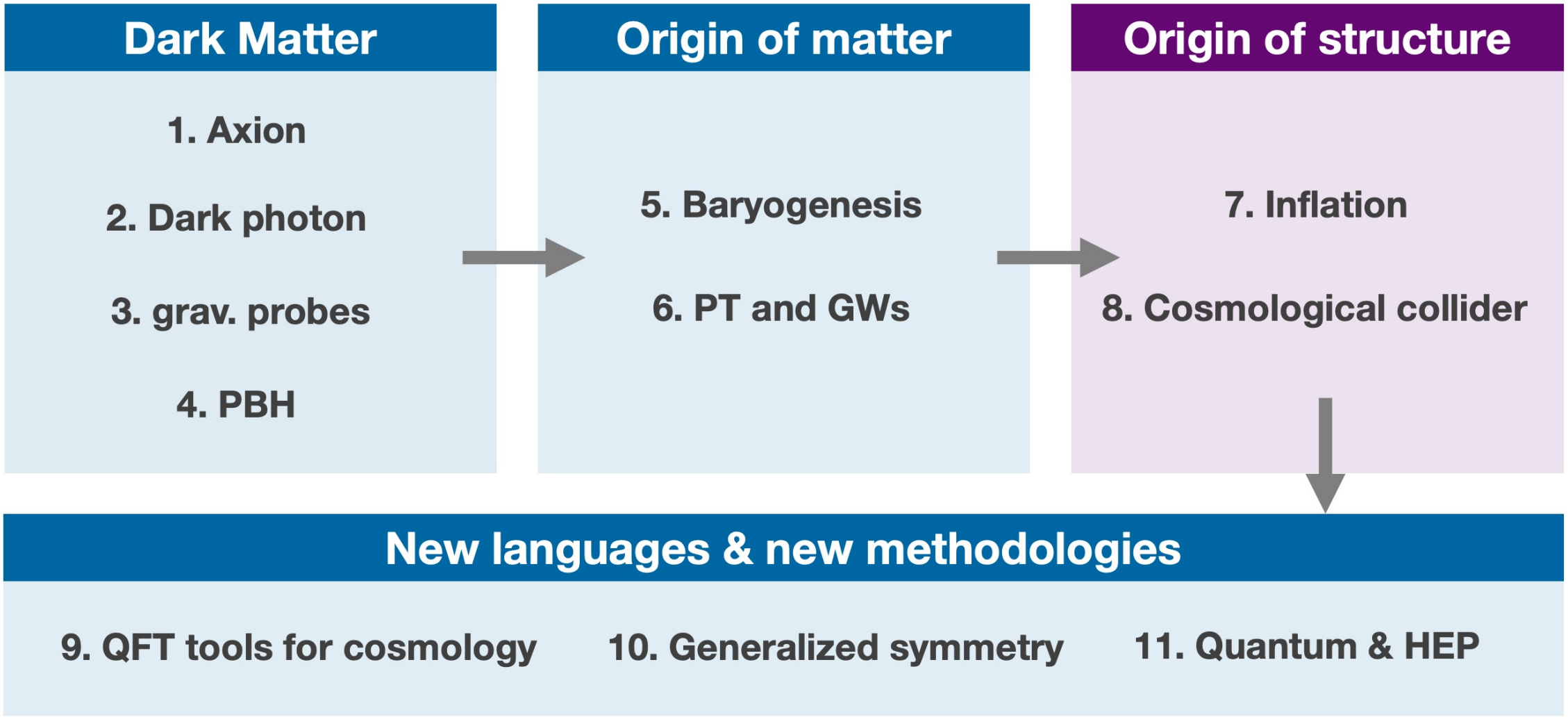
Image credit: NANOGrav



From Huaike Guo

- A golden era for GW physics in 2030s
  Next-Gen ground telescopes + mHz (Taiji/Tianqin/LISA)
  Recent nHz GW already created a huge wave of new ideas
- A stochastic GW background of primordial origin (not SMBH binaries) would be a clear BSM signal
  However, challenging to tell!
- Caution required using GW to probe new physics
  Stellar BBH background
  Mass gap vs. Formation channel
  [Randall, ZX, 1708.08569, 1802.05718, 1805.05335, etc, Xian Chen+]
- Complications and fun with phase transitions and GWs
  Suppression from soundwave lifetime **[Guo+, 2007.08537]**
  Improved calculation of bubble wall velocity
  [Huang+, 2011.12903, 2211.13142, etc.]
  Importance of simulation **[Ligong Bian+]**
  Particle dynamics with first-order phase transition **[Kepan Xie+]**

Outline


Dark Matter
1. Axion
2. Dark photon
3. grav. probes
4. PBH
Origin of matter
5. Baryogenesis
6. PT and GWs
Origin of structure
7. Inflation
8. Cosmological collider
New languages & new methodologies
9. QFT tools for cosmology
10. Generalized symmetry
11. Quantum & HEP

Cosmic inflation | current status

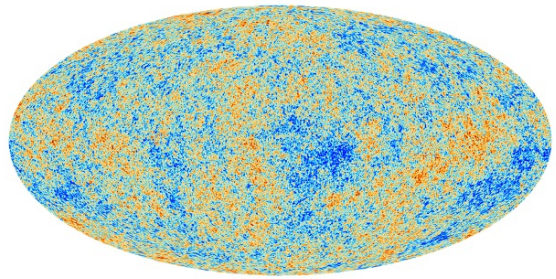
- The uniformity of large-scale fluctuation
  calls for a causal explanation that goes beyond the scope of SM:
  primordial cosmology

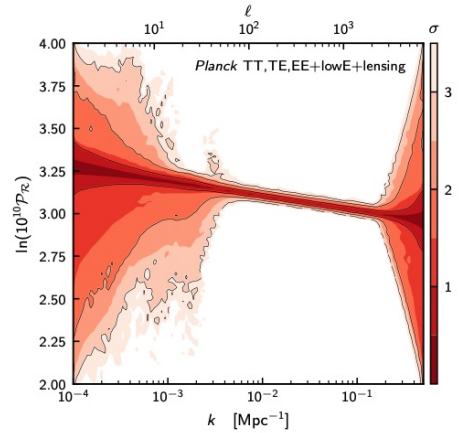
- Inflation remain the leading paradigm
  A phase of near-exponential expansion, H ~ 10^{14} GeV
  Quantum fluctuations generated by the expansion source LSS

- Power spectrum very well measured at the CMB scales [0.1% precision!]

- Tensor mode unobserved, very sensitive to energy scale! [CMB S4?, AliCPT, LiteBIRD]

- Two classes of inflation models: large- & small-field
  Large-field: model realization easy; large tensor modes;
  potential tension with QG considerations [WGC, DC]
  Small-field: lower energy scale, very flat potential, typically tuned





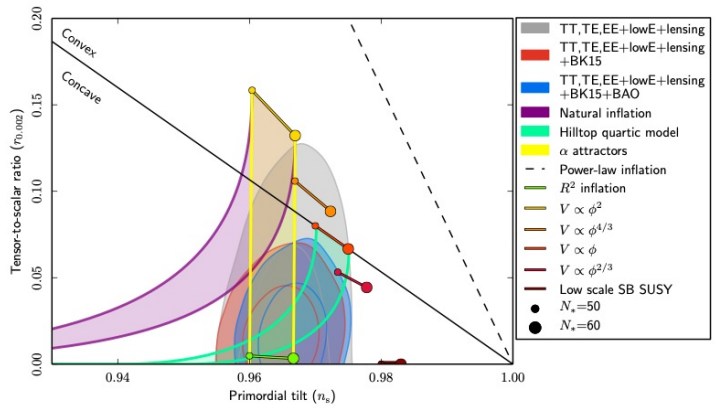


Image credit: Planck 2018

Cosmic inflation | particle physics opportunities

- Current observation suggests very flat inflation potential
  Theory-wise: hard to maintain flatness for long [QG: DC & WGC]

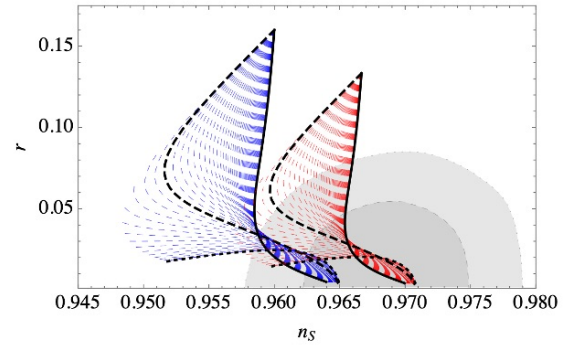
- Model building challenge for particle theory **[Works by Tianjun Li etc.]**

- Likely not single-field slow-roll for entire inflation: new possibilities!
  A inflaton-scalar mix can suppress the tensor-to-scalar ratio
  [An+., 1706.09971, Iyer+, 1710.03054, Reece+, 2204.11869]
  The PGW does not tell the inflation scale, nor the inflation itself
  Phase transitions during inflation **[An+, 2009.12381, 2304.02361, etc]**

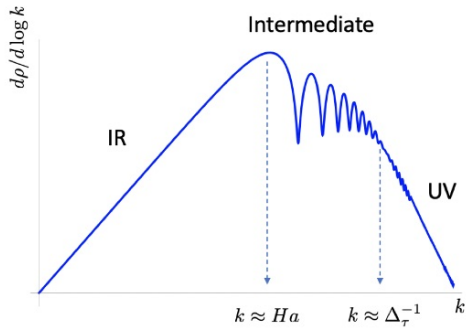
- Non-Gaussianity: not detected yet, but has to be there
  A guaranteed signal: equilateral non-G at percent level, gravitational coupling among inflatons! **[Chen 1002.1416 for a review]**
  Given the weakness of gravity, reasonable to expect larger non-G from non-gravity interactions

- More high-scale BSM physics: alternative-to-inflation? Stringy effects?
  Eternal inflation: a dynamical realization of anthropic argument

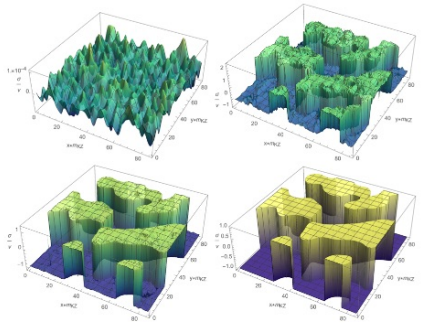
Talks by Jianxin Lu, Ning Chen, Lianbao Jia, Shi-Ping He, …



An+: 1706.09971

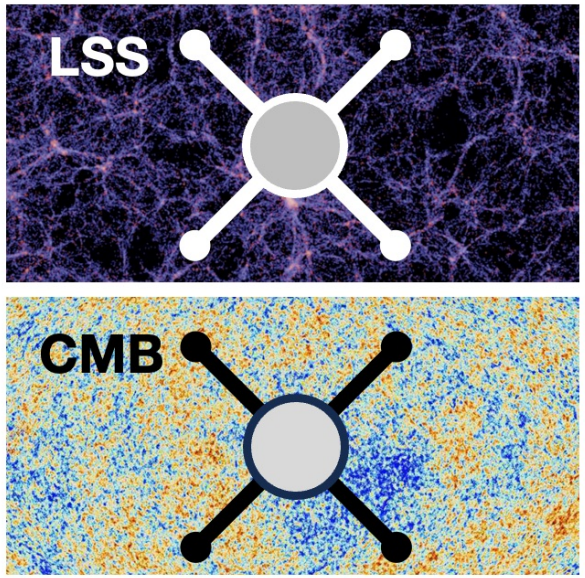


An+: 2009.12381



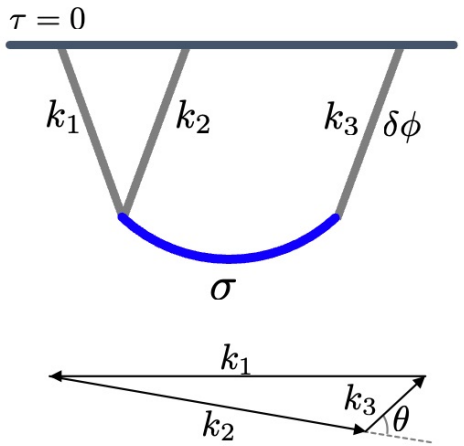
An+: 2304.02361

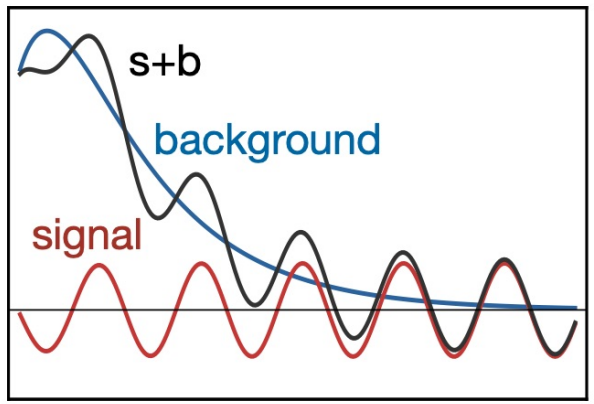
Cosmological collider



- Inflation scale H ~ 10^{14} GeV => Cosmic Schwinger effect
  Active spontaneous particle production of mass m ~ H
- After production, redshifted and diluted, but can imprint the correlation functions of scalar/tensor fluctuations
  [Chen, Wang, 0911.3380; Arkani-Hamed, Maldacena, 1503.08043 and many more]
- In the squeezed limit, the massive particle produces an oscillatory feature in the logarithm of momentum ratios

$$\mathcal{S}_{\rm signal}(k_1,k_2,k_3) \sim B\left(\frac{k_1}{k_3}\right)^L \sin\left[\omega \log\left(\frac{k_1}{k_3}\right)+\delta\right]$$



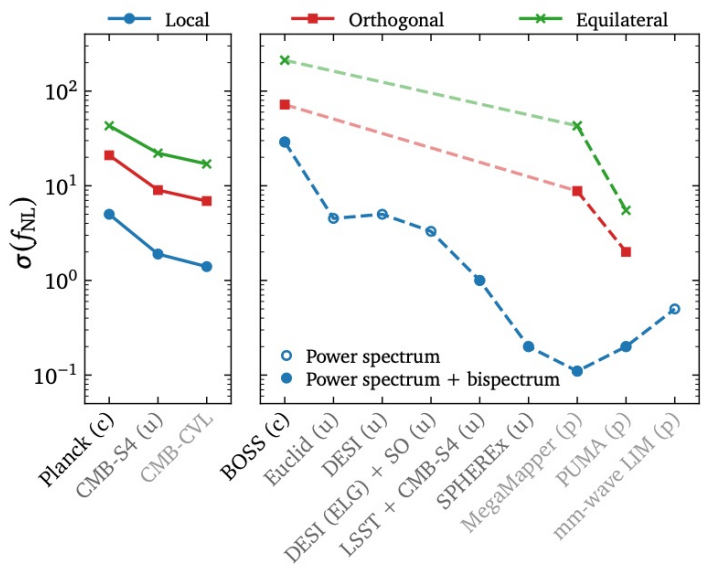


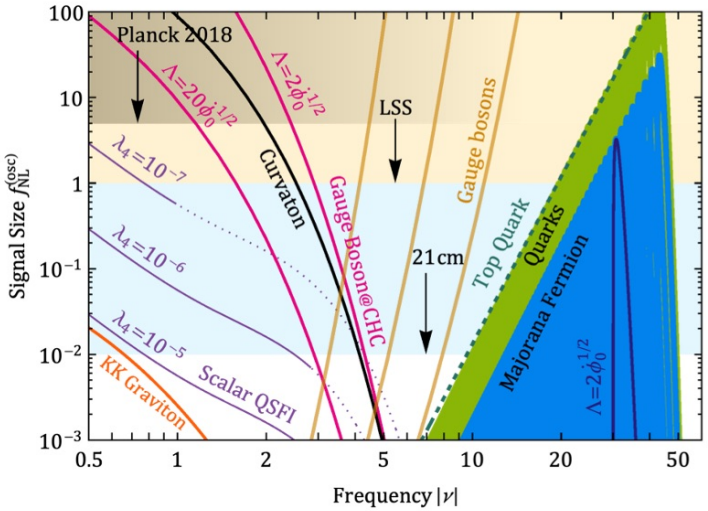
log of momentum ratio

- CC signal contains rich physics:
- mass / spin / interaction type
- The log tells the spacetime expansion

Cosmological collider | particle phenomenology

[Snowmass: 2203.08128]





[Wang, ZX, 1910.12876]

- The future LSS and 21cm observations will expand parameter space by orders of magnitudes. New chances!
- New data analysis techniques; signal search in real data
  [Sohn+: 2404.07203, Cabass+: 2404.01894]
- Standard model + neutrino phenomenology
  [Chen, Wang, ZX, 1610.06597, 1805.02656 etc.]
- Generic large signals nontrivial, importance of chemical potential **[Wang, ZX, 1910.12876, 2004.02887]**
- Many BSM models explored, but more remain untouched
  Parity violation **[Liu+, 1909.01819, etc]** DM **[Chen, Fan, Li, 2303.03406, etc]**
- Beyond single-field slow-roll:
  Cosmological Higgs collider **[Lu, Wang, ZX, 1907.07390]**
  Leptogenesis **[Cui, ZX, 2112.10793]**

Outline

Dark Matter	Origin of matter	Origin of structure
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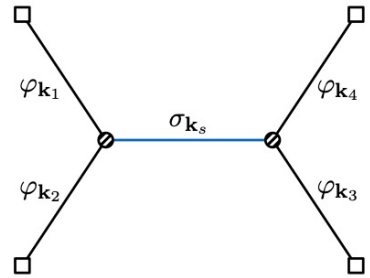
2. Dark photon	6. PT and GWs	8. Cosmological collider
3. grav. probes		
4. PBH		

New languages & new methodologies

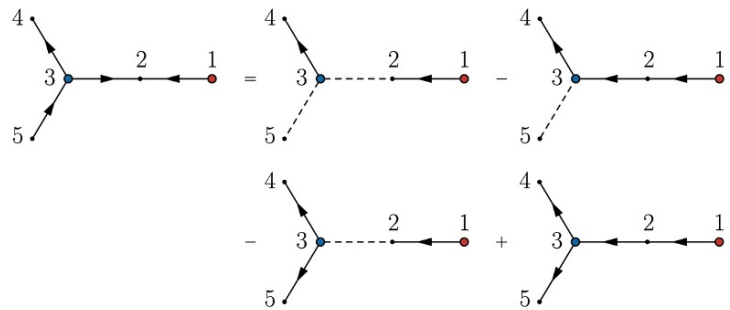
9. QFT tools for cosmology
10. Generalized symmetry
11. Quantum & HEP

QFT tools for astrophysics and cosmology

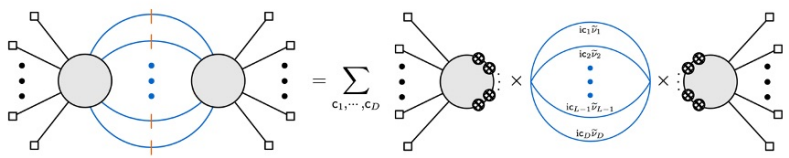
- Growing interests in cosmological amplitudes
  Very complicated, but many new progresses! **[Chen, Wang, ZX, 1703.10166]**
- Cosmological bootstrap and related diff eq techniques
  use of symmetry, locality, and (bulk) unitarity
  [Arkani-Hamed+, 1811.00024, etc] [Chen, Feng, 2401.00129]
- Tree graphs essentially solved!
  Partial Mellin-Barnes representation + family-tree decomposition
  [Qin, ZX, 2205.01692, 2208.13790, 2301.07047; ZX, Zang, 2309.10849]
- Loop-level news:
  Complete 1-loop shapes **[ZX, Zhang, arXiv:2211.03810; Liu, Qin, ZX, 2407.12299]**
  All-loop factorization and cutting rules **[Qin, ZX, 2304.13295, 2308.14802]**
- FRW conformal amplitudes; Cosmological polytopes
  [Arkani-Hamed+, 2312.05303, Fan, ZX, 2403.07050, He+, 2407.17715]
- Other related QFT studies: GW waveforms and LSS EFT
  [Bern, Cheung+, Senatore+]



Single massive exchange



Family-tree decomposition



All-loop factorization and cutting rule

Talks by Song He, etc.

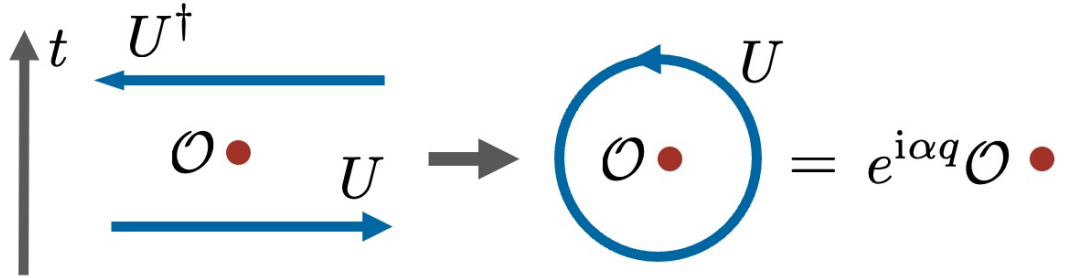
Generalized symmetry | basic ideas

- New perspectives on an old concept:
  Global symmetry acts locally as a topological operator
- Extended charged objects
  => Higher form symmetry
- Example: 4d pure Maxwell
  Conservation of electric/magnetic lines:
  Electric/magnetic 1-form symmetry

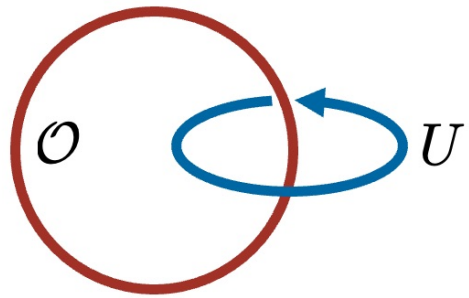
$$\partial_\mu F^{\mu\nu} = 0 \qquad \partial_\mu \widetilde{F}^{\mu\nu} = 0$$

- Pure Maxwell: $U(1)_e^{(1)}$ spontaneously broken
  => massless Goldstone = photon
  Pure SU(3): unbroken => confinement
  [order par for QCD confinement?]

[See Gomes, 2303.01817, Brennan+, 2306.00912, Bhardwaj+, 2307.07547, Luo+, 2307.09215, Iqbal, 2407.20815, etc for pedagogical reviews]



$$U^\dagger \mathcal{O}(x) U = e^{i\alpha q}\mathcal{O}(x)$$



Electric 1-form sym:

$$A \to A + \Lambda \text{ with } \mathrm{d}\Lambda = 0$$

Symmetry operator measures the electric flux:

$$U = e^{i\alpha \int \mathrm{d}F}$$

Charged operator = Wilson loop

$$\mathcal{O} = e^{iq \int \mathrm{d}A}$$

Generalized symmetry | applications

- Ambiguity of standard model gauge group $\quad \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y/\Gamma$
  $\Gamma \in \{1, \mathbb{Z}_2, \mathbb{Z}_3, \mathbb{Z}_6\}$
  [Tong, 1705.01853]
- Implication: axion couplings to SM gauge fields and obstruction to GUT
  [Cordova, Hong, Wang, 2309.05636]

$$S \supset \frac{i\ell_1}{8\pi^2}\int \frac{a}{f}F_1 \wedge F_1 + \frac{i\ell_2}{8\pi^2}\int \frac{a}{f}\mathrm{tr}(F_2 \wedge F_2) + \frac{i\ell_3}{8\pi^2}\int \frac{a}{f}\mathrm{tr}\,(F_3 \wedge F_3)$$

- Axion as the gauge field for instanton number conservation
  [Aloni+, 2402.00117]
- Understanding quantum gravity: No global symmetry ⇔ All charge rep should be present
  [Rudelius, Shao 2006.10052, Heidenreich, 2104.07036]
- New noninvertible symmetry of SM and reinterpretation of ABJ anomaly
  [Choi, Lam, Shao, 2205.05086]
- Comment: A new language, mostly rephrasing known results
  However, a historical lesson from the Hamiltonian formalism

Quantum & HEP

- Quantum information-based language has been very useful for understanding:
  Blackhole entropy: Ryu-Takayanagi formula
  Blackhole information paradox and the island proposal

- New applications in particle physics and cosmology?

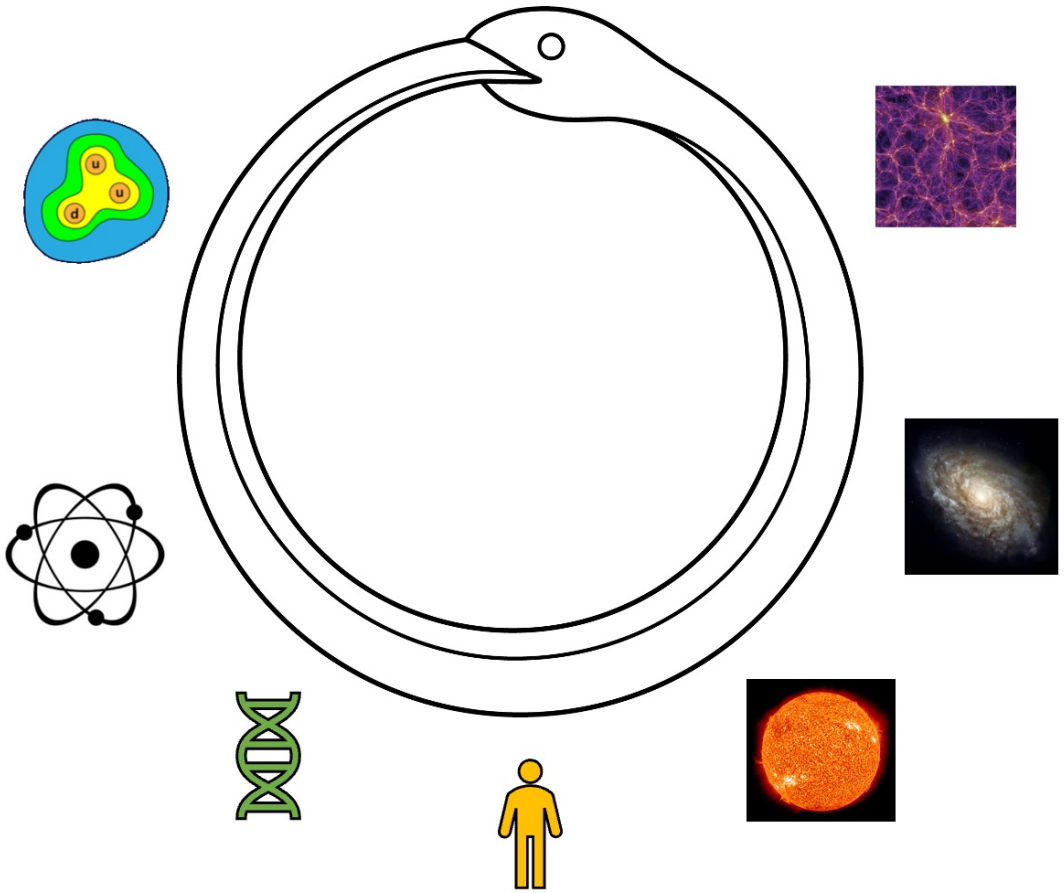
- Positivity bounds from entropic arguments
  Proof of the weak gravity conjecture **[Cheung, Liu, Remen, 1801.08546]**
  Constraining higher-dim operators in (SM)EFT **[Cao, Ueda, 2201.00931; Cao, Kan, Ueda, 2211.08065]**

- Testing Bell inequalities
  With collider observables **[Bi, Cao, Zhang, 2307.14895, Cheng, Han, Low, 2311.09166, 2407.01672]**
  With cosmology **[Ning, Sou, Wang, 2305.08071, Sou, Wang, Wang, 2405.07141, etc.]**

- A new formulation of wave DM with quantum-optics-inspired language
  [Cheong, Rodd, Wang, 2408.04696]

Talks by Hideki Okawa, Qing-Hong Cao, Ming Huang, Ying-Ying Li, Hao Zhang, etc

Final thoughts



Sheldon Glashow: cosmic ouroboros

- Two keywords in recent years
  - Multimessager => New methodology
  - Precision cosmology => New techniques
- Many new possibilities! --- “Anything goes?”
- Big questions remain unanswered!
  - Theory-wise: mysteries of SM
  - Obsv-wise: nature of DM and DE, Origin of neutrino mass, origin of matter and structure
- A revolution ahead of us? Are we ready for it?
  - Deep understanding of existing results
  - Open-minded about new languages

Thank you!